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Summary of DARPA Suboff Experimental Program Data

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Experimental measurements of the flow fields from an axi-symmetrical body with and without appendages were made in the Carderock Division, Naval Surface Warfare Center (CDNSWC) and Tracor Hydronautics Ship Model Basin (HSMB). These experimental data are intended to serve as the data base for the Computational Fluid Dynamics (CFD) validations and other submarine related flow field analyses and was identified as the Defense Advanced Research Projects Agency (DARPA) SUBOFF project. Previous reports have documented various aspects of this SUBOFF test program. This report summarizes all collected data set in tabulated formats and serves as the final database for future submarine flow research.

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ABSTRACT

Experimental measurements of the flow fields from an axi-symmetrical body with and without appendages were made in the Carderock Division Naval Surface Warfare Center (CDNSWC) and Tracor Hydronautics Ship Model Basin (HSMB). These experimental data is intended to serve as the data base for the Computational Fluid Dynamics (CFD) validations and other submarine related flow field analyses and was identified as the Defense Advanced Research Projects Agency (DARPA) SUBOFF project. Previous reports have documented various aspects of this SUBOFF test program. This report summarizes all collected data set in tabulated formats and serves as the final database for future submarine flow research.

ADMINISTRATIVE INFORMATION

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INTRODUCTION

The Submarine Technology Program (STP) Office of DARPA funded a concerted and coordinated Computational Fluid Dynamics (CFD) Program to assist in the development of advanced submarines for the future. The SUBOFF project provides a forum for the CFD community to compare the numerical predictions of the flow field over an axisymmetric hull model with and without various typical appendage components with experimental data.

Detailed and accurate flow measurements around an axisymmetric body were conducted in the wind tunnel and towing basins. In addition, resistance and force measurements for maneuvering were also performed in the towing tanks. Brief summaries of different phases of this SUBOFF experimental program are presented in the Experiment Program Summaries section. This includes the discussion of the tests for circumferential wake surveys, static pressure surveys, boundary layer surveys, and surface pressure/shear stress distributions. Detail discussion of each test series can be found in the specific reports listed in the references on page 11. Papers have also been presented on the SUBOFF data and results at conferences and symposiums.

EXPERIMENT PROGRAM SUMMARIES

The SUBOFF experiment program is divided into four phases: the initial model definition, model construction and instrumentation, test plan design and pretest analysis, and data acquisition. A brief

discussion of each of these phases is presented below. Detailed discussion of the subject matter can be found in the referenced reports.

PHASE I - GEOMETRIC CHARACTERISTICS OF DARPA SUBOFF MODELS

The model geometry for the two SUBOFF models, DTRC Model 5470 and 5471, are identical. The two models differ only in the location of the surface pressure taps. Each model component is described by equations giving either the axial and radial values for axisymmetric components or the Cartesian coordinates (x,y,z) for non-axisymmetric components, (Ref. 1). Figure 1 shows a general layout of the model.

Hull

The model has an overall length of 14.2917 ft (4.356 m). The hull is composed of a fore-body length of 3.3333 ft (1.016 m), a parallel mid-body length of 7.3125 ft (2.229 m), an aft-body of length of 3.6458 ft (1.111 m), and an end cap length of 0.3125 ft (0.095m).

Bridge Fairwater

The fairwater is located on the hull at top dead center of the model with its leading edge positioned at x=3.0330 ft (0.924 m) and the trailing edge at x=4.2413 ft (1.293 m) for a total length of 1.2083 ft (0.368 m). The bridge fairwater is closed at top with an ellipsoid. In addition to the sail cap, the bridge fairwater is defined in terms of a fore-body, a parallel mid-body, and an aft-body.

Stern Appendages

The stern appendages consist of four identical appendages mounted on the model hull at angles of zero degree (top dead center) 90, 180 and 270 degrees. The basic stern appendage assembly can be shifted to attach to the hull at three different axial positions: designated as the upper-stream, base, and the down stream positions.

Ring Wings

Two ring wings have been designed for the SUBOFF models. The wings, designated as Ring Wing 1 and Ring Wing 2, have the same section shape and differ only in their angle of attack.

Ring Wing Struts

Strut supports are necessary in mounting the ring wings to the hull. Four separate, identical struts are mounted equally spaced along the hull girth. The struts are attached at the same axial position, x=13.589 ft (4.142 m) and have the same section profile. At the inner surface of each wing, the struts are contoured to match the surface.

PHASE II - INSTRUMENTATION

The instrumentation required during this SUBOFF program depended on the type of measurements. For the wind tunnel (AFF) tests, detail pressure and velocity surveys were needed; force measurements were performed in the towing tanks; and stability and control for maneuvering characteristics were conducted in the Rotating Arm Facility. A brief discussion of the instrumentation employed in the test program is presented below.

Wind Tunnel (AFF) Tests

A. Anechoic Flow Facility and Model Set-Up

The Anechoic Flow Facility (AFF) is a closed-loop, atmospheric pressure wind tunnel with a maximum air speed of 200 fps (61 mps). The tunnel has a 10 to 1 area contraction upstream leading to an 8 ft (2.4 m) square by 13.75 ft (4.2 m) long closed-jet test section. The contraction and closed-jet have 1.75 ft (0.53 m) fillets to reduce any secondary flows associated with the corners. The closed-jet opens into a large acoustically lined chamber 23.5 ft (7.1 m) square and 21 ft (6.4 m) long.

The DARPA model was mounted in the AFF with the nose and most of the parallel mid-body located within the closed jet, as shown in Figure 2. The aft-section of the model extended into the open-jet anechoic chamber. This position minimized tunnel blockage effects on the flow around the primary interest region: the stern. Pretest analyses by Liu et al (Ref. 5) demonstrated that the effect of the open and closed jet model positioning had minimal effect on the flow parameters if the reference pressure and velocity were selected in the open jet area, corresponding to $x/L = 0.88$.

The model was supported by two thin NACA 0015 struts located at $x/L = 0.24$ and 0.63. The strut bases were mounted below the tunnel floor for minimal flow disturbance. The model end of the strut was connected to a gimble secured to the model strongback. For added model stability, two 1/16-inch

cables were attached laterally to the strut and anchored to the tunnel wall. This support arrangement allowed the freedom required to align the model for various angles of attack or drift.

B. Pressure Taps

For both DTRC Model 5471 (the Wind Tunnel Model) and DTRC Model 5470 (the Towing Tank Model), a number of pressure taps were located on the hull surface (Ref. 1). On both models, the pressure taps were located on the hull surface (H), the fairwater surface (FW) and the baseline stern appendage surface (SA). On Model 5471, taps were also located on the fairwater/hull intersection (FH) and at the intersection surface of baseline stern appendage/hull (AH). In addition, surface pressure taps were located on both ring wings. A total of 222 surface pressure taps were located on the wind tunnel Model 5471. Table 1 presents the surface pressure tap identification scheme for the Wind Tunnel model.

C. Pressure Transducer

The pressure taps were made of 0.063-inch outside diameter and 0.03125-inch inside diameter stainless steel tubing sanded flush to the surface. The pressure measuring system was a set of five rotary pressure scanning units, operating in parallel. Each unit had a silicon diaphragm, differential pressure transducer attached to 48 mechanically scanned measurement ports. The analog output signal was conditioned, amplified, filtered, and finally connected to the A/D converter of the computer - MASSCOMP. The pressure data were low pass filtered at 10 KHz and sampled at 1 KHz for 100 ms on each tap (Ref. 4).

D. Hot Wire Anemometer

The velocity measurement system utilized standard hot film techniques to obtain the magnitudes and directions of the velocity vectors. Both single and 3-component probes were used in the survey. Single element probe is used in the boundary layer surveys while 3-component probe were used for the wake surveys. A TSI Model IFA-100 Intelligent Flow Analyzer with Model 150 anemometers and Model 157 signal conditioning unit, was used for instantaneous velocity components.

E. Traversing System

A traversing system was designed and constructed to move velocity or pressure probes efficiently in the model's stern region. The probe position was controlled in the axial, angular, and radial directions.

The traversing unit, shown schematically in Figure 2, allowed a probe to be positioned anywhere within an annular volume 59 in (1.5 m) long and from 3 in (7.6 cm) to 28 in (71 cm) in radius. As shown in Figure 2, the traversing unit was mounted inside the anechoic chamber directly behind the model. This mounting location provided easy access to the model's stern region. Ward and Gowing (Ref. 4) provide a complete description of the traversing system and its full capabilities.

Towing Tank Tests

Resistance on SUBOFF model was measured in two towing tanks - on Carriage II of NSWCCD and HSMB of Tracor Hydronautics, Inc. The difference was in their model support - NSWCCD used single strut model support (Ref. 8) while HSMB used twin smaller model struts for the measurement (Ref. 3). Standard block gages were used in both facilities.

Stability and control tests for maneuvering were conducted in the HSMB for vertical and horizontal plane Planar Motion Mechanism tests (Ref. 3). Rotary coefficients were performed in the NSWCCD Rotating Arm Facility (Ref. ????).

PHASE III - TEST PLAN AND PRETEST ANALYSIS

The experimental SUBOFF program was presented in Ref. 2. It consisted of the following:

A. AFF Experiments

The AFF experimental program involved the measurement of the flow quantities along an axisymmetric body. They were the three components of mean velocities and their turbulence intensities; two Reynolds stresses; boundary layer surveys along the upper meridian at five locations; static wall pressures along four meridians of the body; skin frictions at selected meridians/locations; and static pressure distributions in the near wake. In the wake survey experiments, both circumferential (spatial) and limited time varying (at selected spatial locations), were measured.

Eight basic model configurations were tested for the SUBOFF Program as outlined in Ref. 2 (configurations 1 through 8). However, limited additional measurements (mostly pressure measurements) were taken when the model was configured for basic tests. They were named as AFF-9 through 19 for additional information of interests. The basic designated AFF-* numbers are:

1. axisymmetric body at 0° angle of attack and drift (designated as AFF-1-*)

2. axisymmetric body with fairwater (designated as AFF-2-*)
3. axisymmetric body with four identical stern appendages (designated as AFF-3-*)
4. axisymmetric body with fairwater at angle of attack and zero drift (designated as AFF-4-*)
5. axisymmetric body with fairwater at drift and zero angle of attack (designated as AFF-5-*)
6. axisymmetric body with ring wing 1 (designated as AFF-6-*)
7. axisymmetric body with ring wing 2 (designated as AFF-7-*)
8. axisymmetric body with fairwater and four identical stern appendages at zero angle of attack and zero drift (designated as AFF-8-*)

These basic model configurations and additional configurations are summarized in Table 1:

The actual wake and pressure surveys are summarized in Tables 2 and 3 respectively. Definition of measurement location is presented in various tables in Ref. 1. A brief summary of the pressure tap identification scheme is shown in Table 4.

B. Towing Tank Tests

Resistance tests were conducted in the NSWC/CD Towing Tank on Carriage II. The model configurations are:

Config. 1	Bare hull only
Config. 3	Hull with four stern appendages
Config. 8	Hull with sail and four stern appendages
Config. 6	Hull with ring wing #1
Config. 7	Hull with ring wing #2

Test speed ranges were limited from 6 to 18 knot model speeds.

Resistance tests with same configurations listed above were repeated in the HSMB. In addition, PMM tests were also conducted in the HSMB for the following configurations:

a) Vertical plane statics - angle of attack variation, $-20° < \alpha < 20°$
   - ➢ Configuration 1
   - ➢ Configuration 6

b) Horizontal Plane Statics - Angle of Drift Variation, $-20° < \beta < 20°$
   - ➢ Configuration 2

C. Pretest Analysis

To ensure the quality of all experimental data measured in the AFF, potential flow and boundary layer computer programs were used to determine the effects of tunnel blockage, the supporting struts, the open jet and the procedure to align the model with the flow in the wind tunnel. The results of these pre-test analyses were then used to guide the experimental setup and tunnel reference velocity selection. Detailed discussion of this analysis is presented in Ref. 5.

PHASE IV - PART I : AFF DATA ACQUISITION AND DATA FILE STRUCTURES

A. AFF Velocity Uncertainty Analysis

In Ref. 6, Blanton et al. estimated the uncertainties associated with using the hot-film measurement system. The estimates included bias uncertainties and precision uncertainties. Bias uncertainties were found by perturbing the data reduction equation with estimates of individual uncertainty. The bias uncertainties were due to (1) temperature, (2) probe alignment, (3) analog to digital conversion, (4) speed calibration, and (5) angle calibration which are all summarized in Table 5.

Precision uncertainty was determined for both boundary-layer type measurements and wake-survey type measurements. In the boundary-layer simulation, 30 data values were collected while the hot-film sensor remained stationary in both the free-stream (TI=0.5%) and the turbulent wake (TI=4%). In the wake survey estimate, the probe was moved to different radii and q in a 30-minute time interval, then returned to its initial position. The precision uncertainty for these conditions, summarized in Table 6, is much smaller than the bias uncertainties shown in Table 5.

B. AFF Pressure Uncertainty

Gowing, (Ref. 7), identified the major sources of error in the pressure and shear stress measurements. Misalignment of the reference Pitot tubes and temperature drifts in the electronics were the major sources of pressure measurement error. The Pitot tube readings were compared during testing to check for misalignment and thermal drift in the electronics was compensated by repeated calibrations at the elevated temperatures. Over an estimated tunnel maximum temperature rise of 7°C, the true pressure coefficients will be within +0.01 and -0.0085 of the measured value. The pressure coefficient for the model nose will be within +0.013 and -0.012 of the measured value. For small friction coefficient values, the greatest error occurred in measuring the small difference between two pressure coefficients. For larger friction coefficients, the major error sources were the accuracy limits of the published calibrations for Preston tubes and flow misalignment. Overall, Gowing (Ref. 7) estimated the true friction coefficients to be within ±0.0002 of their measured values.

C. AFF Flow Data and File Name

AFF model configurations, Table 1, and test plan, Tables 2 and 3, were combined to provide a summary table for all tests conducted for the SUBOFF program. The tests were labeled in Test.*** and

grouped in the directory tree according to Table 7. The actual test number corresponding to the detail test configurations were further grouped as: Table 8 - wake surveys; Table 9 - static pressure surveys in the wakes; Table 10 - boundary layer surveys; Table 11 - surface pressure measurements on and around the control surfaces; Table 12 - skin friction measurements.

All AFF test data were grouped into three presentation formats as shown in Table 13a-e. A brief explanation of the format follows:

a) Tables 13a and 13b are velocity measurements
   - First line describes type of measurement, model configuration, and measurement plan
   - Second line indicates number of data points in the file
   - Third line to the end of file are the normalized velocities from measurements
   - The parameters listed in the columns are shown as the last line of the Table; i.e., r/R,θ, 3-D velocities, 3-D fluctuation velocities, and Reynolds stresses

b) Tables 13c and 13d are surface pressure measurements
   - First line indicates the type of measurement: P for surface pressure and S for skin friction measurements. Location of pressure taps are labeled according to Table 4
   - Second line is the number of data points
   - Third line to the end of file are the normalized pressure data
   - The parameters listed in the columns are shown as the last line of the Table; i.e., Tap ID, x/L, and C_p

c) Table 13e is the static pressure survey file
   - First line indicates the model configuration in the survey.
   - Second line is the number of data points
   - Third line to the end of file are the data
   - The parameters listed in the columns are shown as the last line of the Table; i.e., r/R, Angle, and C_p

D. AFF data Analysis

Flow data from the AFF experiments have been used in a number of CFD analyses. The published papers, from NSWC/CD, are listed in Refs. 10 to 14.

PHASE IV - PART II : TOW TANK DATA ACQUISITION AND DATA FILE STRUCTURES

Tow tank resistance tests are presented in Refs. 3 and 8. As an example, Table 14 is reproduced from Ref. 8. Investigations of the stability and control characteristics for several configurations are presented in Ref. 3 and 9.

All test data are grouped into the SUBOFF database with file structure as shown in the Table 15. Data is presented in ASCII format with headings that describe the nature of the data that follows. All test data are stored in the companion PC Zip diskette with this report.

CONCLUSION

A SUBOFF database was established in the Navy's Hydrodynamics and Hydroacoustic Center (H/HTC). These test data were intended for CFD validation and other flow research on body of revolution with and without various types of appendages. They will serve as the data resource for the future submarine research and development.

ACKNOWLEDGMENT

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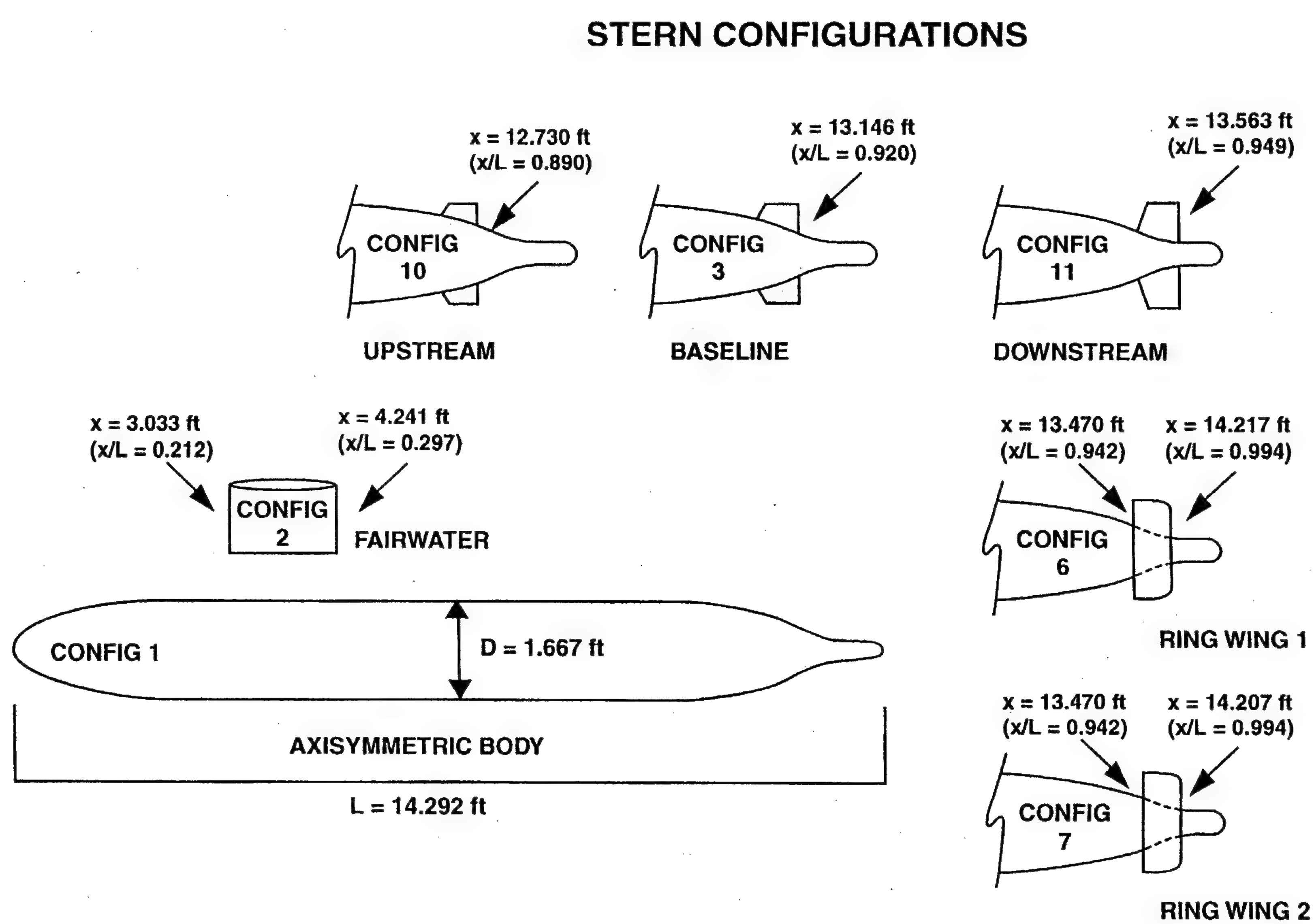

Fig. 1 Schematic of DARPA SUBOFF Model components and stern configurations.

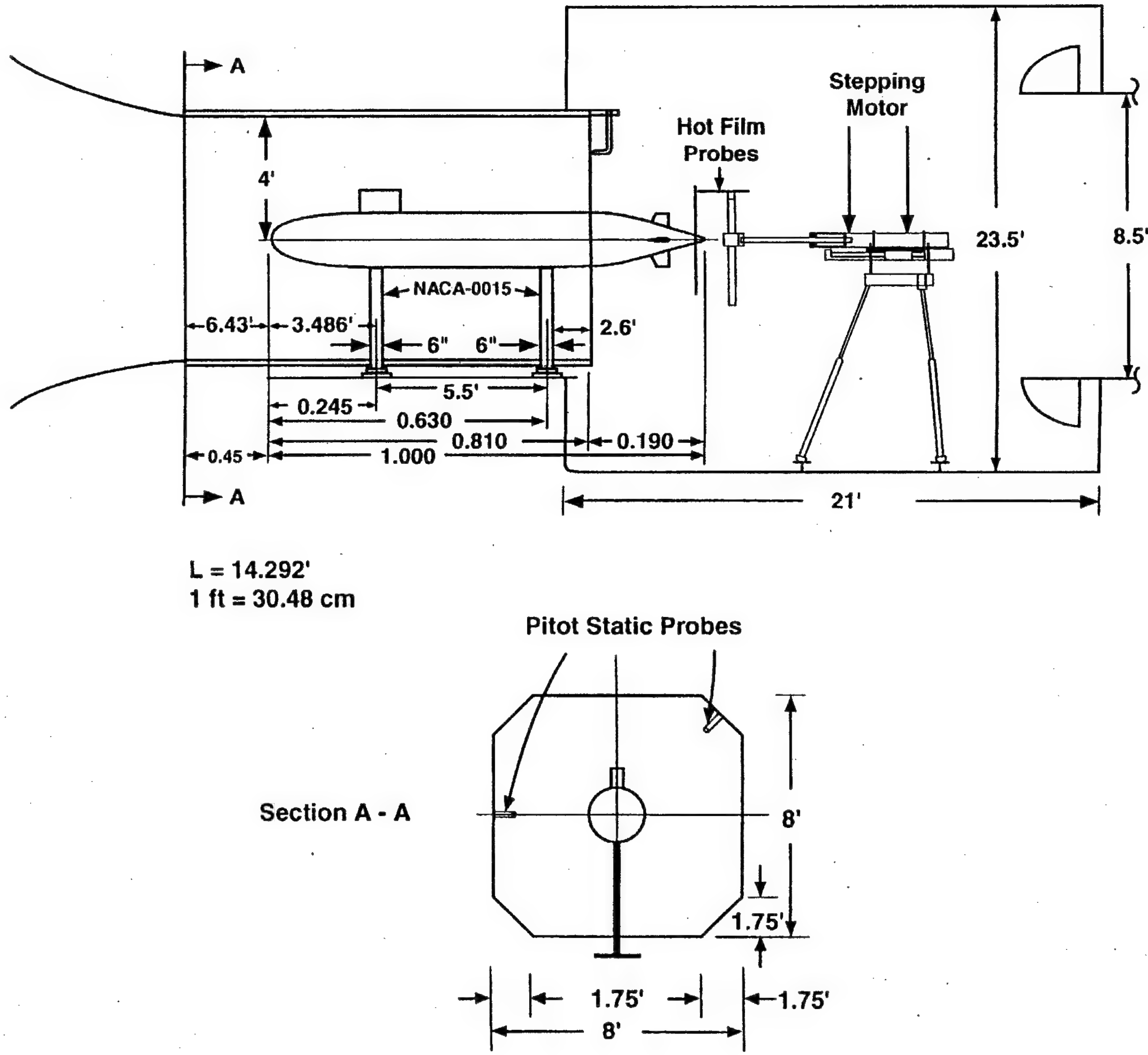

Fig. 2 Schematic view of Model in closed- and open-jet test section.

Table 1. Model Configuration Definition.

Config. No.	Axisym Body	Fair-water	4 Stern Appendages Base line	Up stream	Down stream	Ring Wing # 1	Ring Wing # 2	Angle of Attack 0°	2°	Angle of Drift 0°	2°
1	x							x		x	
2	x	x						x		x	
3	x		x					x		x	
4	x	x							x	x	
5	x	x						x			x
6	x					x		x		x	
7	x						x	x		x	
8	x	x	x					x		x	
9	x								x	x	
10	x			x				x		x	
11	x				x			x		x	
12	x	x				x		x		x	
13	x	x					x	x		x	
14	x		x						x	x	
15	x	x	x						x	x	
16	x					x			x	x	
17	x						x		x	x	
18	x	x				x			x	x	
19	x	x					x		x	x	

Table 2. Velocity and Pressure Survey Planes (x/L).

Model Config.	Survey Planes : x/L								
	0.875	0.904	0.927	0.956	0.978	0.996 Or 0.997	1.040	1.096	1.200
1	VP	V,VP,PP	VP	VP	V,VP,PP		V	V, PP	V, PP
2		V, PP			V, PP		V	V, PP	V
3					V, PP		V, PP	V, PP	V
4		V,VP			V, VP			V	
5		V,VP			V, VP			V	
6					V, VP	V, VP	V	V	V
7					V, VP	V, VP	V	V	V
8					V, PP		V, PP	V, PP	V
9					V, VP				
10					V				
11					V				

Note: V = Circumferential Wake Survey with 3-component Hot-Wire Anemometer
VP = Boundary Layer Survey with single element Hot Wire Anemometer
PP = Static Pressure Survey with Static Pressure Probe
The radial location of the survey points are defined in Reference 2, Table 3

Table 3. Surface Pressure Surveys.

Model Config.	Surface Pressure Tap Designator											
	HU	HP	HS	HL	FH	FW	AH	SA	W*P	W*U	W*S	W*L
1	P,S	P,S	P,S	P	P,S		P,S					
2	P,S	P,S	P,S	P,S	P,S	P,S	P					
3	P,S	P	P	P			P,S	P,S				
4	P	P	P	P	P	P	P					
5					P	P						
6	P								P	P	P	P
7	P								P	P	P	P
8	P	P	P	P	P,S		P,S	P,S				
9	P	P	P	P	P		P					
10												
11												
12	P								P	P	P	P
13	P								P	P	P	P
14	P	P	P	P			P	P				
15							P	P				
16	P	P	P	P					P	P	P	P
17	P	P	P	P			P		P	P	P	P
18	P	P	P	P			P		P	P	P	P
19	P	P	P	P			P		P	P	P	P

Note: P = Surface Pressure Measurements
S = Skin Friction Measurements

Table 4. Surface Pressure Tap Identification.

Pressure Tap Identification	Pressure Tap Location	Number of Pressure Taps
HU_i	Upper hull surface	21
HP_i	Port side hull surface	7
HL_i	Lower hull surface	7
HS_i	Starboard side hull surface	7
Fw_i	Fairwater (Sail) surface	30
FH_i	Fairwater/Hull intersection region	76
SA_i	Upper rudder stern appendage	33
AH_i	Stern appendage/hull intersection region	41
	Total Surface Pressure Taps	222
	Ring Wing Surface Pressure Taps	
$W*U_i$	Top of wing, both inner & outer surfaces	19
$W*P_i$	Portside of wing, inner & outer surfaces	6
$W*L_i$	Bottom of wing, inner & outer surfaces	6
$W*S_i$	Starboard of wing, inner & outer surfaces	6
	Total Surface Pressure Taps	37

Table 5. Velocity Bias Uncertainty.

	u/Uref %	v/Uref %	w/Uref %
Temperature	0.32	0.32	0.32
Probe Alignment	-	0.50	0.50
Analog to Digital Conversion	0.07	0.13	0.12
Speed Calibration	2.12	1.76	0.88
Angle Calibration	0.53	1.31	1.43
Total (Root Sum Square)	2.21	2.28	1.79

Table 6. Velocity Precision Uncertainty.

	u/Uref %	v/Uref %	w/Uref %
Boundary Layer, Free-Stream (TI=0.5%)	0.04	0.04	0.06
Boundary Layer Turbulent Wake (TI=4%)	0.28	0.16	0.20
Wake	0.16	0.06	0.04

Table 7. Data Directory Organization.

Config. No.	Model Configuration	Directory Name	Remarks
1	Bare Hull	AFF1-P-Surface	hu,hp,hs,hl,fh,ah
		AFF1-PP-Static	x/L=0.904,0.978,1.096,1.2
		AFF1-S-Shear	
		AFF1-VP-BL	x/L=0.904,0.927,0.956,0.978
		AFF1-V-Wake	x/L=0.904,0.978,1.040,1.096,1.2
9	Hull +2° Pitch	AFF9-P-Surface	hu,hp,hs,hl,fh,ah
		AFF9-VP-BL	x/L=0.978
		AFF9-V-Wake	x/L=0.978
2	Sail Only	AFF2-P-Surface	hu,hp,hs,hl,fh,fw,ah
		AFF2-PP-Static	x/L=0.904,0.978,1.096
		AFF2-S-Shear	
		AFF2-V-Wake	x/L=0.904,0.978,1.040,1.096,1.2
4	Sail +2° Pitch	AFF4-P-Surface	hu,hp,hs,hl,fh,fw,ah
		AFF4-VP-BL	x/L=0.904,0.978
		AFF4-V-Wake	x/L=0.904,0.978,1.096
5	Sail +2° Drift	AFF5-P-Surface	fh,fw
		AFF5-VP-BL	x/L=0.904,0.978
		AFF5-V-Wake	x/L=0.904,0.978,1.096
3	Base Appendages	AFF3-P-Surface	hu,hp,hs,hl,ah,sa
		AFF3-PP-Static	x/L=0.978,1.040,1.096
		AFF3-S-Shear	
		AFF3-V-Wake	x/L=0.904,0.978,1.040,1.096,1.2
10	UpStream Append.	AFF10-V-Wake	x/L=0.978
11	DnStream Append.	AFF11-V-Wake	x/L=0.978
6	Ring Wing #1	AFF6-P-Surface	wu,wp,ws,wl
		AFF6-VP-BL	x/L=0.978,0.996
		AFF6-V-Wake	x/L=0.978,0.997,1.040,1.096,1.2
12	Sail+ RW#1	AFF12-P-Surface	wu,wp,ws,wl
16	RW#1+2° Pitch	AFF16-P-Surface	hu,hp,hs,hl,wu,wp,ws,wl
18	Sail+ RW#1+2° Pitch	AFF18-P-Surface	hu,hp,hs,hl,wu,wp,ws,wl
7	Ring Wing #2	AFF7-P-Surface	wu,wp,ws,wl
		AFF7-VP-BL	x/L=0.978,0.997
		AFF7-V-Wake	x/L=0.978,0.997,1.040,1.096,1.2
13	Sail+ RW#2	AFF13-P-Surface	wu,wp,ws,wl
17	RW#2+2° Pitch	AFF17-P-Surface	hu,hp,hs,hl,wu,wp,ws,wl,ah
19	Sail+ RW#2+2° Pitch	AFF19-P-Surface	hu,hp,hs,hl,wu,wp,ws,wl,ah
8	Sail+Base Append.	AFF8-P-Surface	hu,hp,hs,hl,fh,ah,sa
		AFF8-PP-Static	x/L=0.978,1.040,1.096
		AFF8-S-Shear	
		AFF8-V-Wake	x/L=0.978,1.040,1.096,1.2
14	Append.+ 2° Pitch	AFF14-P-Surface	hu,hp,hs,hl,fh,ah,sa
15	Sail+Append.+ 2° Pitch	AFF15-P-Surface	ah,sa

Note: AFF*P-Surface Surface Pressure Measurement
AFF*PP-Static Circumferential Static Pressure Survey

Table. 7 (Continued)

Table 7. Data Directory Organization

AFF*S-Shear	Skin Friction Measurement
AFF*VP-BL	Boundary Layer Velocity Profile Survey
AFF*V-Wake	Circumferential Wake Survey

Table 8. Wake Survey : Model Configurations and Test Numbers.

Model Configuration	Config No.	x / L	r / R_{max} 0.25	0.30	0.35	0.40	0.45	0.50	0.60	0.72	0.92	1.20	1.60	2.0
Bare Hull	1	0.904	-	-	-	-	510	511	512	513	514	515	516	-
		0.978	004	005	006	007	517	008	009	518	519	520	521	522
		1.040	523	524	525	526	527	528	529	530	531	532	533	534
		1.096	010	011	012	013	-	014	015	536	537	538	539	540
		1.200	-	017	018	019	541	020	021	542	543	544	545	546
Hull + 2° Pitch	9	0.978	840	841	842	843	844	845	846	847	848	849	850	851
Sail	2	0.904	-	-	-	-	034	600	035	601	036	037	038	039
		0.978	040	041	042	043	602	044	045	046	047	048	049	050
		1.040	603	604	605	606	607	608	609	610	611	612	613	614
		1.096	051	052	053	615	616	054	055	617	056	057	058	059
		1.200	-	061	062	618	619	063	064	620	065	066	067	068
Sail + 2° Pitch	4	0.904	-	-	-	-	-	170	171	681	172	173	174	175
		0.978	176	177	178	179	682	180	181	182	183	184	185	186
		1.096	-	188	189	683	684	190	191	685	192	193	194	195
Sail + 2° Drift	5	0.904	-	-	-	-	-	207	208	700	209	210	211	212
		0.978	-	214	215	216	701	217	218	219	220	221	222	223
		1.096	-	225	226	702	703	227	228	704	229	230	231	232
Baseline Appendages	3	0.978	098	099	100	101	650	102	103	104	105	106	107	108
		1.040	109	110	111	652	653	112	113	654	114	115	116	117
		1.096	118	119	120	655	656	121	122	657	123	124	125	126
		1.200	-	128	129	658	659	130	131	660	132	133	134	135
Upstream Appen	10	0.978	880	881	882	883	884	885	886	887	-	-	-	-
Dnstream Appen	11	0.978	920	921	922	923	924	925	926	927	-	-	-	-
Fully Appended	8	0.978	300	301	302	303	790	304	305	306	307	308	309	310
		1.040	791	792	793	794	795	796	797	798	799	800	801	802
		1.096	311	312	313	803	804	314	315	805	316	317	318	319
		1.200	-	806	807	808	809	810	811	812	813a	813b	813c	813d
Ring Wing #1	6	0.978	238	239	240	241 *	-	-	-	-	-	-	-	-
		0.997	243	244	245	246	247	248	249	-	-	-	-	-
		1.040	721	722	723	724	725	726	727	828	-	-	-	-
		1.096	251	252	253	254	255	256	257	-	-	-	-	-
		1.200	-	260	261	262	263	264	265	729	-	-	-	-
Ring Wing #2	7	0.978	271	272	273	274 *	-	-	-	-	-	-	-	-
		0.996	276	277	750	278	279	280	281	-	-	-	-	750 a
		1.040	-	752	753	754	755	756	757	758	-	-	-	-
		1.096	283	284	285	286	287	288	289	760	-	-	-	-
		1.200	-	292	293	294	295	296	297	761	-	-	-	-

Note: Ring Wings also have r/R=0.22 surveys :

	x/L=.978	.997	1.040	1.096
Ring Wing #1:	237	242	720	250
Ring Wing #2:	270	275	751	282

Table 9. Static Pressure Survey : Model Configurations and Test Numbers.

Model Configuration	Config No.	x / L	r / R_{max}											
			0.25	0.30	0.35	0.40	0.45	0.50	0.60	0.72	0.92	1.20	1.60	2.0
Bare Hull	1	0.904	-	-	-	-	-	-	554	555	556	557	558	559
		0.978	560	561	562	563	564	-	565	566	567	568	569	570
		1.096	571	572	573	574	575	-	576	577	578	579	580	581
		1.200	582	583	584	585	586	-	587	588	589	590	591	592
Sail	2	0.904	-	-	-	-	-	-	073	628a	074	075	076	-
		0.978	078	079	080	081	628b	082	-	084	-	086	087	088
		1.096	089	090	091	628c	628d	092	093	628e	094	095	-	-
Baseline Appendages	3	0.978	138	139	140	141	668a	142	143	144	145	146	147	148
		1.040	-	-	-	668b	668c	-	-	668d	-	-	-	-
		1.096	158	159	160	668e	161	-	162	668g	163	164	-	-
Fully Appended (Sail + Baseline Appendages)	8	0.978	824a	-	824b	824c	824d	824e	824f	824g	824h	824i	824j	824k
		1.040	825a	825b	825c	825d	825e	825f	825g	825h	825i	825j	825k	825l
		1.096	826a	826b	826c	826d	826e	826f	826g	826h	826i	826j	-	-

Table 10. Boundary Layer Velocity Profiles and Test Numbers.

Model Configuration	Config No.	Probe Type	x / L	Circumferential Angle (Deg)					
				0	45°	90°	180°	270°	315°
Bare Hull	1	3-D	0.904	002	473	474	-	475	476
			0.927	477	478	479	480	481	482
			0.956	483	484	485	486	487	488
			0.978	003	489	490	491	492	493
		X	0.875	450	451	452	-	453	454
			0.904	455	456	457	458	459	460
			0.927	461	462	463	464	465	466
			0.956	467	468	469	470	471	472
Hull + 2° Pitch	9	3-D	0.978	830	-	-	-	-	-
Sail + 2° Pitch	4	3-D	0.904	168	670	-	-	-	671
			0.978	169	672	-	-	-	673
Sail + 2° Drift	5	3-D	0.904	199	205	690	691 *	-	202
			0.978	200	206	692	693 *	-	203
Ring Wing #1	6	3-D	0.978	235	-	-	-	-	-
			0.996	236	-	-	-	-	-
Ring Wing #2	7	3-D	0.978	268	-	-	-	-	-
			0.997	269	-	-	-	-	-

Note: The angle for these two tests is 135 deg.

Table 11. Surface Pressure and Skin Friction Measurements.

Model Configuration	Config. No.	HU	HP	HS	HL	FH	AH	SA	FW	WU	WP	WS	WL
Bare Hull	1	022	547	548	549	23	24	-	-	-	-	-	-
BareHull + 2° Pitch	9	852	853	854	855	856	857	-	-	-	-	-	-
Sail	2	621	622	623	624	069	625	-	070	-	-	-	-
Sail + 2° Pitch	4	686	687	688	689	196	689 a	-	197	-	-	-	-
Sail + 2° Drift	5	–	-	-	-	233	-	-	234	-	-	-	-
Baseline Appendages	3	661	662	663	664	-	136	137	-	-	-	-	-
Append. + 2° Pitch	14	962	963	964	965	-	960	961	-	-	-	-	-
Sail + Base Append.	8	814	816	815	817	820	818	819	-	-	-	-	-
Sail+Append.+ 2° Pitch	15	-	-	-	-	-	970	971	-	-	-	-	-
Ring Wing #1	6	267	-	-	-	-	-	-	-	266a	266b	266c	266d
Sail + RW#1	12	940	-	-	-	-	-	-	-	941	942	943	944
RW#1 + 2° Pitch	16	984	985	986	987	-	-	-	-	980	981	982	983
Sail+RW#1+2° Pitch	18	1000	1001	1002	1003	-	1008	-	-	1004	1005	1006	1007
Ring Wing #2	7	299	-	-	-	-	-	-	-	298a	298b	298c	298d
Sail + RW#2	13	950	-	-	-	-	-	-	-	951	952	953	954
RW#2 + 2° Pitch	17	994	995	996	997	-	998	-	-	990	991	992	993
Sail+RW#2+2° Pitch	19	1010	1011	1012	1013	-	1018	-	-	1014	1016	1015	1017

Note : Definitions of HU, HP, etc. are listed in Table 1.

Table 12. Skin Friction Measurements.

Model Configuration	Config. No.	HU	HP	HS	HL	FH	AH	SA	FW
Bare Hull	1	025	550	551	-	552	553	-	-
Sail	2	071 a	071b	071 c	071d	627	-	-	626
Baseline Appendages	3	665	-	-	-	-	666	627	-
Sail + Base Append.	8	-	-	-	-	823	821	822	-

Table 13. Data File Structures.

Table 13a. Wake Survey Data File.

8/14/89 Wake Survey x/L = 0.904 r/R = 0.46 Bare Hull
181

r/R	Angle	V_x	V_r	V_t	V_x'	V_r'	V_t'	Re_{xr}	Re_{xt}
0.4600	0.00	0.3510	-0.0937	0.0215	0.0523	0.0384	0.0495	9.9077E-04	-8.2627E-05
0.4600	2.00	0.3499	-0.0916	0.0206	0.0496	0.0382	0.0514	9.1268E-04	-7.1843E-05
0.4600	4.00	0.3486	-0.0931	0.0218	0.0510	0.0376	0.0507	8.8125E-04	-1.3235E-04
0.4600	6.00	0.3515	-0.0923	0.0208	0.0530	0.0394	0.0504	1.1128E-03	-1.5181E-04
0.4600	8.00	0.3501	-0.0917	0.0200	0.0531	0.0382	0.0517	1.0147E-03	-1.7426E-04

Table 13b. Boundary Layer Survey Data File.

8/15/89 3-D Boundary Layer Survey x/L = 0.904 45 deg Bare Hull
19

r/R	Angle	V_x	V_r	V_t	V_x'	V_r'	V_t'	Re_{xr}	Re_{xt}
0.4600	45.00	0.3598	-0.0917	0.0268	0.0521	0.0397	0.0490	1.0140E-03	-1.1308E-04
0.4679	45.00	0.3737	-0.0947	0.0244	0.0540	0.0391	0.0504	1.1539E-03	-2.1622E-04
0.4895	45.00	0.4443	-0.1065	0.0270	0.0545	0.0387	0.0509	1.2126E-03	-1.6545E-04
0.5111	45.00	0.5078	-0.1136	0.0307	0.0528	0.0386	0.0500	1.1833E-03	-8.7067E-05
0.5399	45.00	0.5879	-0.1250	0.0287	0.0507	0.0355	0.0458	1.0912E-03	-1.8882E-04

Table 13c. Static Pressure Survey Data File.

AFF-1-pp-0.904 Bare hull static pressure survey
37

r/R	Angle	C_p
0.60	0.0	0.12398
0.60	10.0	0.12364
0.60	20.0	0.12301
0.60	30.0	0.12246

Table 13d. Surface Pressure Measurement Data File.

test aff-1-p-h-taps hu1-hu21
21

Tap ID	x/L	C_p
hu1	0.000000	0.990007
hu2	0.034985	-0.113978
hu3	0.069971	-0.070548
hu4	0.104956	-0.054790
hu5	0.180758	-0.097342

Table 13e. Skin Friction Measurement Data File.

aff-1-s taps hp8-17 bare hull
5

Tap ID	x/L	Skin Friction Coeff.
hp5	0.18076	3.395684e-03
hp8	0.50146	2.673570e-03
hp11	0.74052	2.928076e-03
hp12	0.78134	3.401767e-03
hp17	0.90379	5.701664e-04

Table 14. DARPA SUBOFF Model 5470 DTMB Tow Tank Results.

Config. No.	Model Configuration	Model Speed (knots)	Model Resistance Pound	Model Resistance Newton	Residual Resistance Coeff.	Model Speed (knots)	Resistance Ratio
8	Fully Appended	5.93	23.00	102.3	0.00065		
		10.00	63.80	283.8			
		11.85	87.50	389.2		11.85	1.169
		13.92	118.4	526.6			
		16.00	151.9	675.6			
		17.79	184.6	821.1			
3	Stern Appendages	5.92	21.45	95.41	0.00050		
		11.85	81.35	361.8		11.85	1.087
		17.78	172.2	765.9			
1	Bare Hull	5.92	19.65	87.40	0.00030		
		10.00	54.45	242.2			
		11.84	74.85	332.9		11.84	1.000
		13.92	101.5	451.5			
		16.00	129.7	576.9			
		17.99	156.7	697.0			
6	Ringed Wing #1	5.93	21.05	93.6	0.00055		
		11 85	79.90	355.4			
		17.80	168.1	747.7		11.85	1.067
7	Ringed Wing #2	5.93	21.75	96.74	0.00065		
		11.85	82.00	364.7		11.85	1.096
		17.78	171.3	761.9			

Hull, bridge fairwater and four identical stern appendages all have tripwires installed at 5 percent of chord length.

Ringed wings have no turbulence stimulators applied to them

Table 15. File Directory Structure.

AFF1-PP-static
AFF1-P-surface
AFF1-S-shear
AFF1-VP-bl
- 2comp
- 3comp

AFF1-V-wake
- xol_904
- xol_978
- xol1040
- xol1096
- xol1200

AFF2-PP-static
AFF2-P-surface
AFF2_S-shear
AFF2-V-wake
- xol_904
- xol_978
- xol1040
- xol1096
- xol1200

AFF3-PP-static
AFF3-P-surface
AFF3-S-shear
AFF3-V-wake
- xol_978
- xol1040
- xol1096
- xol1200

AFF4-P-surface
AFF4-VP-bl
AFF4-V-wake
- xol_904
- xol_978
- xol1096

AFF5-P-surface
AFF5-VP-bl
AFF5-V-wake
- xol_904
- xol_978
- xol1096

AFF6-P-surface
AFF6-VP-bl
AFF6-V-wake
- xol_978
- xol1040
- xol1096
- xol1200

AFF7-P-surface
AFF7-VP-bl
AFF7-V-wake
- xol_978
- xol_996
- xol11040
- xol1200

AFF8-PP-static
AFF8-P-surface
AFF-8-V-wake
- xol_978
- xol1040
- xol1096
- xol1200

AFF9-P-surface
AFF9-VP-bl
AFF9-V-wake
- xol_978

AFF10-V-wake
- xol_978

AFF11-V-wake
- xol_978

AFF12-P-surface
AFF13-P-surface
AFF14-P-surface
AFF15-P-surface
AFF16-P-surface
AFF17-P-surface
AFF18-P-surface
AFF19-P-surface